35 GHz RECTENNA IMPLEMENTED WITH A PATCH AND A MICROSTRIP DIPOLE ANTENNA

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ABSTRACT

35 GHz rectennas have been developed using a patch and a microstrip dipole antenna. The power conversion efficiencies from RF to DC were measured as 29% and 39% with an input power of 120 mW. The multi-reflection method developed for the analysis of a mixer was used to analyze the performance of a 35 GHz rectenna using a Ka-band mixer diode. Through this analysis, the effect of the reactive elements of the diode on the efficiency were investigated and the optimum operating circuit conditions and the maximum conversion efficiency were obtained.

I. INTRODUCTION

Microwave power transmission is a viable means to deliver power from space to ground, ground to space, ground to ground, or space to space [1-3]. In the microwave power transmission system, the DC power is first converted into RF power. The RF power is radiated into free space and received by an array of rectifying antennas (rectenna). The RF power is then converted back into DC power by the rectenna circuitry. The rectenna is one of the key components in this system.

The rectenna operating at 2.45 GHz has been studied extensively [1]. The power conversion efficiency has been recorded to be approximately 85%. The frequency of 2.45 GHz was selected to achieve low attenuation through the earth's atmosphere. For the space to space application, the operating frequency can be increased to take the advantage of the smaller transmitting and receiving antennas when transmitting power over large distances. Higher frequency rectennas need to be developed for these systems.

In this work, we have analyzed the performance of 35 GHz rectenna with the multi-reflection method originally developed by Held and Kerr [4] for the analysis of a mixer diode. The equivalent circuit of a Ka-band mixer diode was used for this analysis. Two types of 35 GHz MIC rectennas have been developed using a patch antenna and a dipole antenna. The power conversion efficiencies were measured up to 29% and 39% for the patch and dipole rectennas, respectively.

II. ANALYSIS OF 35 GHz RECTENNA PERFORMANCE

A rectenna consists of an antenna, an impedance matching network, a rectifying diode, and a DC-pass filter. The rectifying diode is a main component that determines the power conversion efficiency of the rectenna. As the operating frequency increases, the junction capacitance of the diode should be decreased to a level that the impedance of the reverse-biased diode is still large enough to rectify the microwave signal. A Ka-band mixer diode with a small junction capacitance was used for the 35 GHz rectenna. The equivalent circuit of the Ka-band diode is shown in Figure 1. The element values of the equivalent circuit are L_W = 0.2 nH, C_p = 0.02 pF, C_{jo} = 0.05 pF, γ = 0.5, I_s = 0.037 pA, V_{br} = 5 Volts, and R_s = 8 Ω. L_W is the lead inductance, C_p is the parasitic capacitance, R_s is the series resistance, C_{jo} is the junction capacitance at zero bias voltage, I_s is the saturation current, and V_{br} is the breakdown voltage.

It is important to know the diode impedance for designing the matching network inserted between the antenna and diode. The diode impedance is a function of the operating power and DC load resistance. The multi-reflection method was used to calculate the power conversion efficiency and effective impedance of the diode for the various operating power levels and DC load resistances. Since the power conversion is a nonlinear process, the power conversion efficiency depends not only on the circuit impedance at the fundamental frequency but also on the circuit impedance at the higher order harmonics. Through many trials, we have found that the efficiency was maximized when the 2nd harmonic impedance of the embedding network of the diode was specified to resonate with L_W. This condition presents a low 2nd harmonic impedance to the terminal A-B in Figure 1-(a). Terminal A-B is the internal P-N junction of the diode. Therefore, the 2nd harmonic impedance was set to $-j$ 87 Ω resonating with L_W (0.2 nH) and all higher order harmonic impedances were set to 0 Ω for the analysis. To investigate how the reactive elements of the diode change the efficiency, a purely resistive diode shown in Figure 1-(b) was analyzed with the multi-reflection method and compared with the actual diode of Figure 1-(a).

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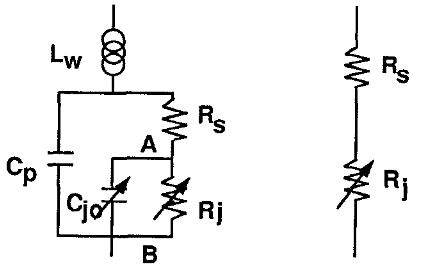

(a) (b)

Figure 1 (a) The equivalent circuit of Schottky diode (b) a resistive diode obtained by omitting the reactive elements of the circuit in (a)

Each point in Figure 2 shows the power conversion efficiency and the diode impedance calculated for a given input power and a DC load resistance. The values in parenthesis show the effective diode impedance at the fundamental frequency and the DC load resistance, respectively. The data calculated for the resistive diode are represented as cross marks and the data for the actual diode are represented as solid circles.

The efficiency of the resistive diode increases to 70% as the operating power level decreases. The optimum DC resistance for the maximum efficiency increases as the power level decreases. In other words, the optimum DC load resistance is small for a high output DC power. This condition is due to limiting the DC output voltage to less than half of V_{br}. The effective diode impedance of the resistive diode is increased following the increase of the DC load resistance at the low operating power region. Therefore, the effect of the series resistance of the diode becomes small compared with the diode effective impedance. This results in a small diode loss at the series resistor and a high conversion efficiency of the rectifier.

However, the effective impedance of an actual diode cannot be increased as the case of the resistive diode. The junction capacitance of the actual diode will limit the highest effective impedance of the diode. If the actual diode is forced to operate with a high effective impedance by using a high DC load resistance, a high current will flow through the junction capacitance resulting in a low power conversion efficiency. According to the calculated results shown in Figure-2, the maximum efficiency of the actual diode follows that of the resistive diode until the optimum DC load resistance is increased to 100 Ω. The maximum efficiency then enters saturation. This saturation occurs because the junction capacitance prevents the DC load resistance from increasing more than 100 Ω. Therefore, the transition to the saturation region gives the optimum design parameters for the maximum conversion efficiency and the maximum output power. We could determine that the optimum diode effective impedance, DC load resistance, and the output power are 40 Ω, 100 Ω, and about 30 mW, respectively. The maximum power conversion efficiency was estimated to be approximately 50% with these design parameters.

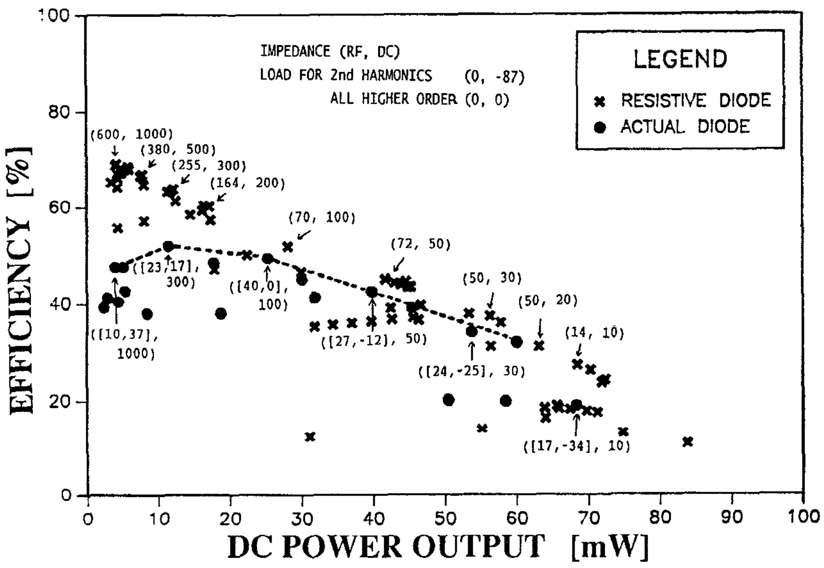

Figure 2 The power conversion efficiency of Ka-band mixer diode calculated with multi-reflection method : parameters of GaAs Schottky diode : $R_S = 8\ \Omega$, $V_{br} = 5$ V, $I_S = 0.037$ pA, $Cj = 0.053$ pF, $\gamma = 0.5$, $L_W = 0.2$, $C_p = 0.02$ pF.

III. DESIGN OF 35 GHz RECTENNAS

Figure 3 shows two rectennas incorporating a patch antenna and a microstrip dipole antenna. The size and the input impedance of the square patch antenna built on a RT/duroid substrate (10 mil thick, $\varepsilon_r = 2.2$) was calculated as 2.6 mm^2 and 220 Ω using the cavity model [5]. The matching network between the antenna and the diode was designed to provide a 40 Ω impedance at the fundamental frequency and a $-j$ 87 Ω impedance at the 2nd harmonic to the diode. The dimension of the matching network were determined to be L1 = 2.39 mm, L2 = 1.16 mm, W1 = 0.35 mm, L3 = 0.81 mm, W2 = 0.1 mm, and S = 0.5 mm. One terminal of the diode was connected to the ground plane via hole. The DC output line was connected to the center of the non-radiating edge of the patch antenna.

The dipole rectenna has two filters connected to the diode. The DC-pass filter was designed to provide an open circuit at the fundamental frequency and the low pass filter was designed to reflect the higher order harmonics and provide a 40 Ω impedance at fundamental frequency to the diode. Both filters were then optimized through the simulation of the rectenna using a computer program called LIBRA. The dimensions of each coplanar strip line filter sections were determined to be L1 = 0.92 mm, L2 = 1.19 mm, L3 = 0.58mm, L4 = 0.18 mm, L5 = 2 mm, W = 1 mm, Z_0(high) = 240 Ω, and Z_0(low) = 130 Ω. The same RT/duroid substrate was used for the dipole rectenna. The length and the width of the microstrip dipole were determined to be 0.46 λ_0 and 0.02 λ_0, and the input impedance was calculated to be 55 Ω [6].

IV. MEASUREMENT OF POWER CONVERSION EFFICIENCY

The power conversion efficiencies were measured using a waveguide array simulator [7] shown in Figure 4 to simulate the array environment. A rectenna was attached to the waveguide expander which was built to expand the cross section of a Ka-band waveguide (WR-28). For the measurement of the dipole rectenna, a quarter-wavelength spacer was inserted between the rectenna and the reflecting plane.

Figure 5 shows the measured efficiency with a 100 Ω load resistance. The efficiency is defined as the ratio of the DC output power to the net input power to the diode. The net input power is the difference between the incident power and the reflected power. The maximum efficiencies measured with the patch rectenna and the dipole rectenna were 29% and 39% respectively at an net input power of 120 mW.

V. CONCLUSION

The power conversion efficiency of the 35 GHz rectenna was analyzed with the multi-reflection method. The maximum efficiency calculated from the equivalent circuit of a Ka-band mixer diode was approximately 50% and the optimum DC resistance was estimated as 100 Ω. Based on this analysis, two types of 35 GHz rectenna were developed using a patch and a microstrip dipole antenna. The power conversion efficiency was measured up to 29% and 39% for a patch rectenna and a dipole rectenna, respectively.

VI. ACKNOWLEDGEMENTS

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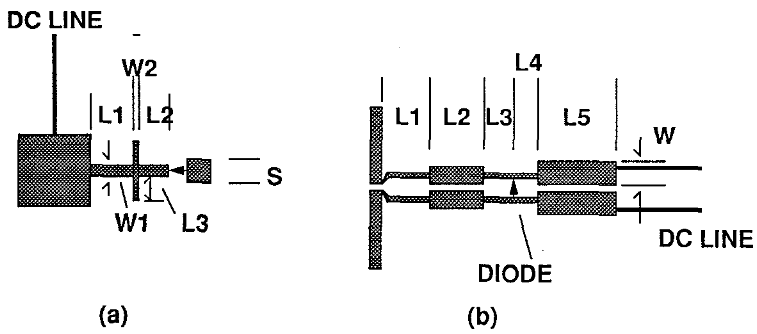

Figure 3 35 GHz rectennas implemented with (a) a patch antenna and (b) a microstrip dipole antenna

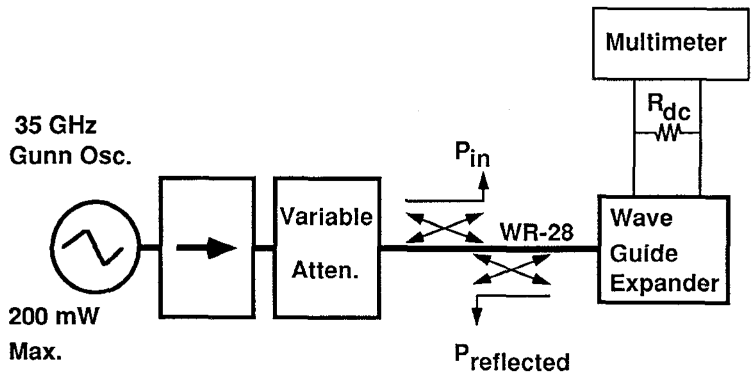

Figure 4. Waveguide array simulator setup for the measurement of the 35 GHz to DC power conversion efficiency

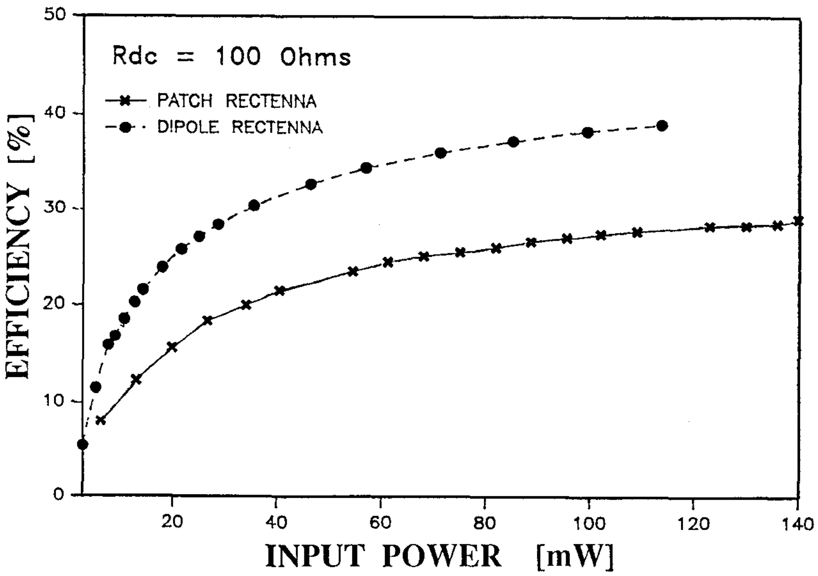

Figure 5 The power conversion efficiency of the 35 GHz rectenna measured with the waveguide array simulator